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(FOR ARTICLES ON THE GEOLOGY OF EAST ANGLIA)

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EDITORIAL

This issue of the Bulletin contains a welcome blend of geological interest. Richard West provides a thought provoking re-interpretation of the depositional context at the Lynford Archaeological Site which was originally described in the 2012 English Heritage publication 'Neanderthals Among Mammoths' edited by Bill Boismier and colleagues*. It will be interesting to see whether this re-interpretation stimulates further debate on this complex and intriguing site. Steve Boreham and Christopher Rolfe continue the Breckland theme, using ground penetrating radar to investigate beneath periglacial patterned ground to establish its sedimentological and soil character. In a change of emphasis, Annika Hoogduin and colleagues build a picture of how bivalve taphonomy works in a modern North Sea beach setting, which has direct relevance to the interpretation of fossil assemblages in East Anglian Late Quaternary coastal sediments. Peter Riches then rounds up the issue with a scholarly analysis of William Smith's problems in correlating parts of the post-Chalk stratigraphy in East Anglia, building on the article by Peter Banham in Bulletin 64.

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* BOISMIER, W.A.. GAMBLE, C. & COWARD, F. (eds) 2012. *Neanderthals Among Mammoths. Excavations at Lynford Quarry, Norfolk.* English Heritage, Swindon. 529 pp.

INSTRUCTIONS TO AUTHORS

Contributors should normally submit manuscripts as word-processor electronic files (MS Word is preferred). When papers are accepted for publication we will request an updated electronic version.

It is important that the style of the paper, in terms of overall format, capitalization, punctuation etc. conforms as strictly as possible to that used in Vol. 65 of the Bulletin. Titles and first order headings should be capitalized, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

References should be arranged alphabetically in the following style.

BALSON, P.S. & CAMERON, T.T.J. 1985. Quaternary mapping offshore East Anglia. *Modern Geology*, **9**, 221-239.

STEERS, J.A. 1960. Physiography and evolution: the physiography and evolution of Scolt Head Island. In: Steers, J.D. (ed.) *Scolt Head Island* (2nd ed.), 12-66, Heffer, Cambridge.

BLACK, R.M. 1988. *The Elements of Palaeontology*. 2nd Ed., Cambridge University Press, Cambridge. 404pp.

We now make pdf versions of all papers for authors (replacing offprints) and for possible future WWW availability. For this reason we prefer illustrations drawn with a computer graphics package, ideally saved in jpeg format. Thick lines, close stipple or patches of solid black or grey should be used with care as they can spread in printing hard copy. Colour reproduction of line drawing or photos is used where it enhances impact. The editor may have diagrams re-drawn professionally and usually the GSN will cover the cost of this. For efficient use of space full use should be made of the width of print on an A4 page when designing diagrams.

The editors welcome original research papers, notes, comments, discussion, and review articles relevant to the geology of **East Anglia** as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

ASPECTS OF THE NEOTAPHONOMY OF THREE SPECIES OF BIVALVE MOLLUSCS COMMON IN THE NORTH SEA

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ABSTRACT

Beach assemblages of Recent marine shells are used to investigate aspects of the palaeoecology and taphonomy of major invertebrate groups. A collection of shells and valves of bivalve molluscs were collected from the North Sea coast of Zandvoort aan Zee, the Netherlands. Three species dominated; Cerastoderma edule (Linné), Spisula subtruncata (da Costa) and Ensis americanus (Binney). All shells of C. edule and S. subtruncata were disarticulated into separate left and right valves, indicating a long residence time on the beach. There were more left valves collected than right valves of these two species, indicating post-mortem hydrodynamic sorting. Borings in C. edule and S. subtruncata included Caulostrepsis taeniola Clarke (domiciles of polychaete annelid worms bored after the death of the bivalve), and Oichnus simplex Bromley and O. paraboloides Bromley, but no shells of the predatory gastropods that made the borings were found. Ensis americanus shells were mostly articulated, some shells still retained soft tissues and none were bored or encrusted, indicating a very recent mass death event, probably storms over the previous weekend. Cerastoderma edule and S. subtruncata have more robust shells than Ensis americanus, which favoured their longer residence on the beach.

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INTRODUCTION

A fundamental concern of the Earth sciences is geological time and geologists use the rock record as an indirect means of investigating time. In particular, we study geological sections as a concrete analogue for the time of interest. Our focus on time means that space is commonly relegated to the face(s) of a section(s). The bedding plane, seen as a line in our section, is studied as a representation of what is actually a plane; as a result the dimension of space is diminished. The reason for this is obvious if we examine any quarry face, road cutting or sea cliff; rocks are more commonly exposed in section rather than in plan. But for studies of palaeoecology or preservation (taphonomy), the bedding plane provides an essential dataset.

Very obviously, the most widely exposed time planes are present-day geomorphic surfaces. This means that analogues of bedding plane phenomena are readily available. Because of their abundance and ease of collectability, the remains of marine invertebrates that are accumulated on beaches may act as a proxy for a fossil assemblage. In particular, they may form the focus of diverse studies of ecology and neotaphonomy, the study of preservation of extant species of organisms, at the organism and community level, thus providing information of direct relevance to studies of palaeoecology and taphonomy (see, for example, Ager, 1963; Schäfer, 1972; Parsons & Brett, 1991; Brenchley & Harper, 1998). Certainly, shells on beaches are generally easier to collect than invertebrate fossils from sedimentary rocks. Criteria influencing the composition of these assemblages are many, some applicable only locally, but must include mode of death, hydrodynamic regime and whether the shell was robust or not.

In this paper, accumulations of bivalve molluscs on the beach of Zandvoort aan Zee, Noord-Holland, the Netherlands, have been used to examine the modes of preservation as a substitute for a death assemblage.

LOCALITY

The specimens discussed herein were collected from the beach north-northeast of Zandvoort aan Zee in Noord-Holland, The Netherlands (Fig. 1), on the North Sea coast. All of our specimens were collected on the beach at Zandvoort on Wednesday, 30th March, 2016, between 9.00 a.m. and 12.00 noon, a ‘geological instant’. Shells were

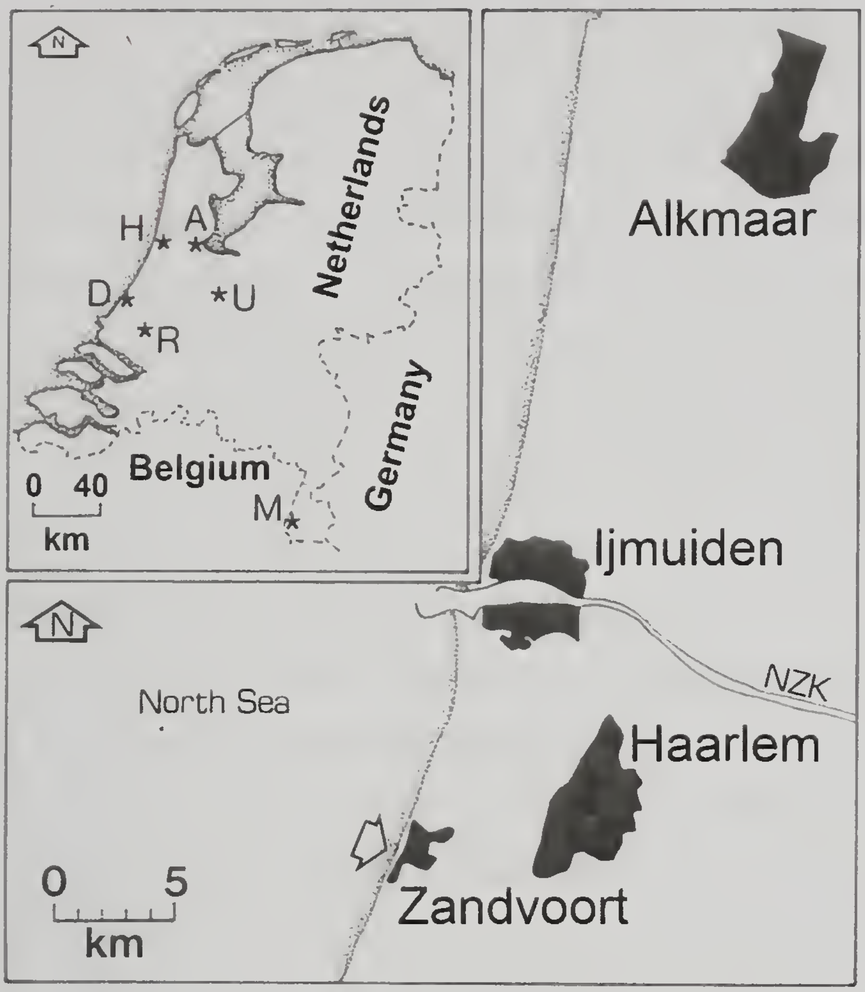

Fig. 1. Outline map of the south coast of Noord-Holland, The Netherlands, with the coastline stippled and settlements marked (after Donovan, 2007). The arrow indicates the study site. NZK is the Noordzee-kanaal. Inset map of The Netherlands shows political boundaries and cities; H, Haarlem, is close to the study site; A, Amsterdam; D, Den Haag (The Hague); M, Maastricht; R, Rotterdam; U, Utrecht.

locally common and found near the strandline. Five separate 'hotspots' with dense accumulations of shells were examined. Common shells and valves were assigned to one of three species. The associated, low diversity fauna on the beach was rich in the disarticulated valves of infaunal, mainly burrowing bivalves as is common at this site (Donovan, 2011), with rare portunid crabs. Other groups that are commonly present, such as gastropods, fishes, *Sepia* (Jongbloed *et al.*, 2016) and *Echinocardium*, were notably absent; only four valves of two species of boring bivalves were noted. The weather was particularly fair and sunny after an Easter weekend of storms, which would have discouraged visitors to the beach on previous days. This was to our advantage, minimising damage to shells and valves by pedestrians, animals and vehicles.

MATERIALS AND METHODS

For collecting the shells and disarticulated valves, a combination of sealable plastic bags, paper towels for wrapping and collection boxes were used. The focus was mainly on three common taxa, namely the common edible cockle (*Cerastoderma edule* (Linné)), cut-trough shells (*Spisula subtruncata* (da Costa)) and American razor shells (*Ensis americanus* (Binney)). Valves of the former two species were commonly preserved with the concave surface oriented down. During collection, other, rarer species were taken for use in determining the diversity of shells/valves on Zandvoort beach (Fig. 2).

The shells were hand collected and bagged by A.L.H. and M.R.V. More fragile or broken specimens were wrapped in paper towelling and stored in the collection boxes to prevent further disintegration. In this way, breakage noted in later assessment was certainly original and not caused by transportation (Flessa *et al*., 1992). Several 'hotspots' of *Ensis americanus* were noticed, most probably washed ashore during the storm of the weekend before and forming a cuspate pattern (Pilkey *et al*., 2011, p. 91). All the shells on these 'hotspots' were collected and stored separately per location.

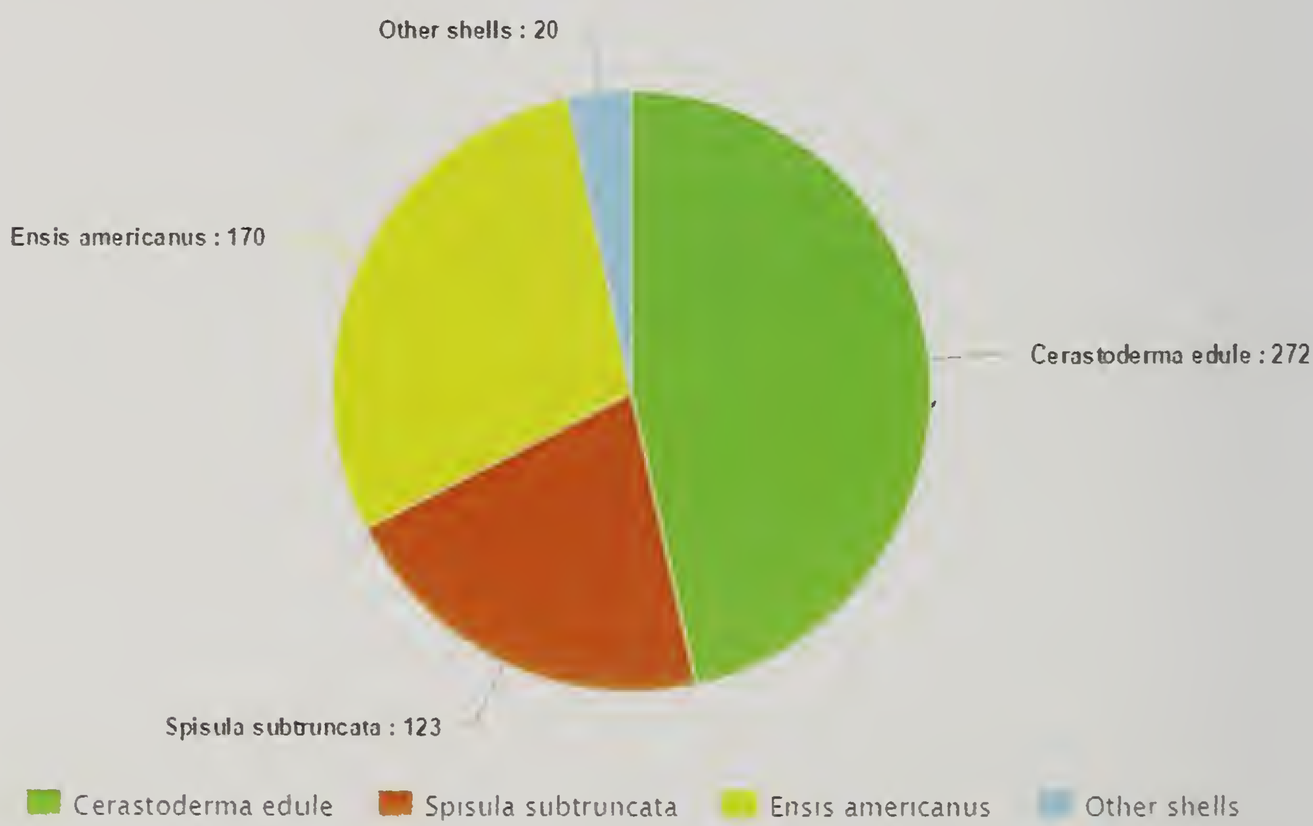

Fig. 2. Relative proportions of collected bivalve molluscs shells and valves; n = 585.

The collected shells were cleaned of sandy sediment before further analysis and identification. Two methods were used for cleaning. For shells of C. *edule* and *S. subtruncata,* valves were first gently washed with tap water, after which any remaining sand was removed using a tissue, a toothbrush or a paintbrush. Articulated shells of *E. americanus* were freshly washed ashore which meant many had the remains of the soft tissues of the dead bivalves inside. These shells were cleaned more rigorously using bleach. Our four collections of razor shells, each from a separate 'hotspot', were split over four plastic buckets containing 0.5 l of domestic bleach topped up with tap water. The shells were left to soak for 48 hours, after which they were removed from the bleach and rinsed with tap water.

Laboratory work began with sorting specimens into species groups and counting them. The left valves were split from the right valves of disarticulated specimens, after which the nature and locations of mechanical damage and borings were noted. Bored shells were laid aside for further inspection. For *E. americanus,* only breakage and articulation were noted because borings were completely absent on these thin-shelled, deep-burrowers (Donovan, 2007, fig. 3). This was the only species where many of the shells were still articulated.

The shells were identified using Barrett & Yonge (1958), Beedham (1972) and Tebble (1976), and the online identification key from Naturalis Biodiversity Center, Leiden, amongst others. Pickerill & Donovan (1998) was used for the identification of predatory borings (*Oichnus* ispp.). Figured specimens were registered in the collections of the Naturalis Biodiversity Center, Leiden (prefix RGM); other specimens were returned to the beach.

RESULTS

Some comment could be made on the pattern of breakage of each of the 500+ specimens examined for this study. Here, however, we concentrate on just the major patterns that are shown by the three common taxa (Fig. 2).

Cerastoderma edule (Fig. 3). Two hundred and seventy two cockle valves were collected; none were articulated. Of these valves, 174 were left and 98 were right. Breakage was common, but 103 valves were undamaged. A large proportion of the

Fig. 3. Valves of *Cerastoderma edule* collected from the beach at Zandvoort aan Zee, North Sea coast, the Netherlands. (A) Hexagonal-shaped *Oichnus paraboloides* boring in a left valve; specimen lost. (B, C) RGM 792 296, left valve with a small *Oichnus simplex* boring close to the broken umbo. (D) RGM 792 298, a large, rounded hole on a damaged umbo of a right valve (compare with Fig. 2B). (E) RGM 792 301, right valve bored by polychaete annelid worms, *Caulostrepsis taeniola*. (F) RGM 792 297, perforation in right valve caused by collapse of a *Caulostrepsis*. (G) RGM 792 302, right valve with particularly well preserved *C. taeniola*. Specimens uncoated; scale bars represent 10 mm.

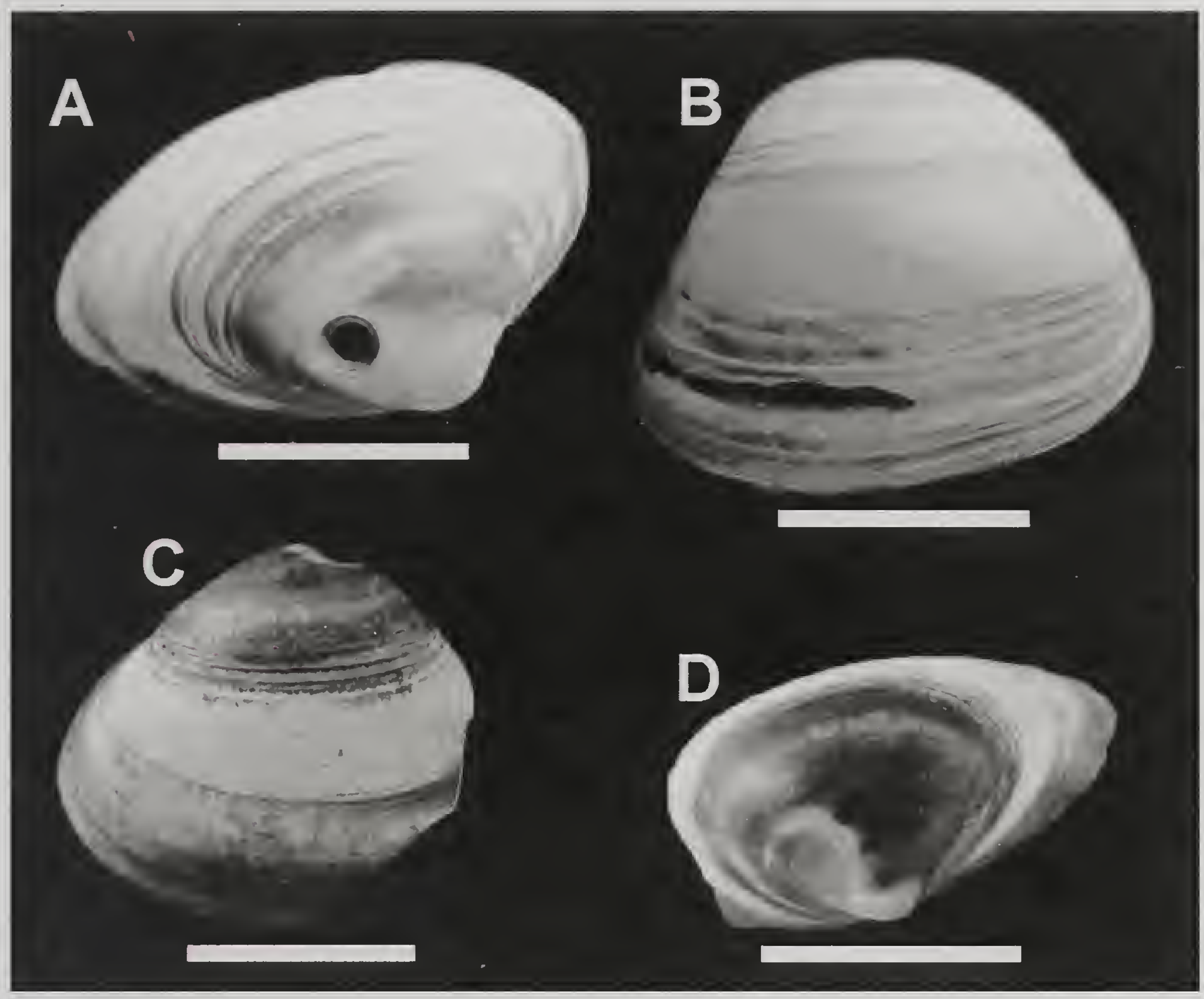

Fig. 4. Valves of *Spisula subtruncata* collected from the beach at Zandvoort aan Zee, North Sea coast, the Netherlands. (A) RGM 792 299, left valve with predatory boring *Oichnus paraboloides* boring close to the umbo. (B) RGM 792 300, an indistinct annelid(?) boring in a right valve. (C, D) RGM 792 303, a broken posterior in a left valve (C) bearing a failed predatory borehole, *O. paraboloides* (D). Specimens uncoated; scale bars represent 10 mm.

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damaged specimens, 112 valves, had a broken umbo (Fig. 3B-D). Posterior breakage was also common in these shells. Borings in the cockles were few and assigned to three ichnospecies. Only one *Oichnus paraboloides* Bromley, 1981, boring was discovered (Fig. 3A); note the hexagonal shape it has because of the boring's interaction with the valve's ribbed surface (this specimen was irretrievably broken after photography). *Oichnus simplex* Bromley, 1981, borings were a little more common, but easily

overlooked because of their small size (Fig. 3B, C). *Caulostrepsis* isp. borings (Fig. 3E-G) were quite common, never occurring on the apex, but always posteriorly or laterally. Well preserved examples were assigned to *Caulostrepsis taeniola* Clarke, 1908 (Fig. 3E, G); note that the keyhole-like boring (Fig. 3F) is probably due to collapse of a *Caulostrepsis*, leaving this unusual hole.

Spisula subtruncata (Fig. 4). There were 123 of the cut-trough shell valves collected, 88 left valves and 35 right valves; like *C. edule*, none of the shells were articulated. Whereas the most common position for breakage in *C. edule* was in the apex, this pattern was essentially absent in *S. subtruncata*, only one valve showing such a pattern of damage. *Spisula subtruncata* was more typically broken in the posterior of the shell (Fig. 4C); of the 123 valves, 45 showed this pattern of breakage. Borings were also more common in *S. subtruncata* than in *C. edule*; there were 15 borings found on 123 valves of the *S. subtruncata* (12.2 %), whereas there were only 13 borings found on 272 valves of the *C. edule* (4.8 %). None of the cut-trough shells preserved evidence of *O. simplex*, but there were eight penetrative boreholes attributable to *O. paraboloides* (Fig. 4A) and a further five uncompleted borings (Fig. 4D), were all found in the umbonal region. Two *Caulostrepsis*-like borings were encountered in our shells (Fig. 4B).

Ensis americanus (Fig. 5). One hundred and seventy specimens of *E. americanus* were collected, of which 153 specimens were articulated. Breakage was fairly common, many shells were cracked antero-posteriorly and dorso-ventral. Boring, however, was absent in all the collected shells, probably because of their deep-burrowing habit. Also, no encrustations were found on the external or internal surfaces even though this beach is well-known for balanids encrusting *Ensis* (e.g., Donovan, 2007, 2011; Donovan *et al.*, 2014).

Other identified shells. The following bivalves were collected at the same time as the above taxa (Fig. 2): *Lutraria lutraria* (Linné); *Petricolaria pholadiformis* (Lamarck); *Mytilus edulis* Linné; *Scrobularia plana* (da Costa); and *Zirfaea crispata* (Linné). The most surprising absence was gastropod shells, particularly as these organisms were presumably responsible for making the predatory *Oichnus* ispp. borings.

Fig. 5. Articulated shell of *Ensis americanus*, RGM 792 304, collected from the beach at Zandvoort aan Zee, North Sea coast, the Netherlands. (A) Inner surface of the articulated shell in 'butterfly' preservation (compare with, for example, Selover *et al.*, 2005, fig. 3; Komatsu *et al.*, 2007, p. 136; Skawina, 2013, fig. 2A). (B) Outer surface of the same shell. Specimens uncoated; scale bars represent 50 mm.

DISCUSSION

We now discuss the principal patterns of taphonomic and palaeoecological interest shown by these bivalves, and interpret them accordingly.

Umbo breakage of Cerastoderma edule (Fig. 3B-D). Breakage of the umbonal region of *C. edule* by a rounded hole is a moderately common phenomenon. This breakage occurred significantly ($p < 0.01$) more often in *C. edule* than in *S. subtruncata* (Tables 1 and 2). The convex, protruding umbo on these valves is considered to be one of the causes for this phenomenon. Further, *Oichnus* ispp. borings are most common in this region ($p < 0.01$; Tables 1, 2) in *S. subtruncata* and may have been a contributing factor in breakage, although no intermediate morphologies were noted. Schäfer (1972, pp. 159-160, fig. 98, lower) summarized previous reports that indicated such holes (= facets) were entirely the result of slow abrasion of *C. edule* where the valve is most curved, occurring in shallow (<30 m) tidal seas with sandy substrates.

Relative proportions of bored valves in C. edule and S. subtruncata (Figs 3A-C, E-G, 4A, B, D). There was a significantly greater percentage of borings in *S. subtruncata* than in *C. edule* (Tables 1 and 2). This could be an indication that the smooth shells of *S. subtruncata* are easier to bore than the ribbed shells of the *C. edule* or simply, in the example of *Oichnus* ispp., a preference of the predators.

Oichnus and Caulostrepsis borings. Identification of the borings and their location suggested site selectivity by the producing organisms. *Oichnus* ispp. borings are most common in the area of the umbo; *Caulostrepsis* isp. were never found in this region and were always located either posteriorly or laterally. Since much of the body of a bivalve is placed in the umbo, the assumption can be made that *Oichnus* ispp. borings are predatory, whereas *Caulostrepsis* ispp. borings are produced post-mortem (that is, the shells of infaunal bivalves are unlikely to be infested by worms during life). *Oichnus simplex* is typically produced by muricids and *O. simplex* by naticids, both groups of predatory gastropods (Pickerill & Donovan, 1998, p. 164; Bromley, 2004, pp. 466-467). *Caulostrepsis* is a domicile produced by a polychaete annelid worm such as *Polydora* (Bromley, 2004, p. 460).

Table 1. Data on the collections of *Cerastoderma edule* (C.E.) and *Spisula subtruncata* (S.S.) discussed herein.

	C.E. left	C.E. right	S.S. left	S.S. right
specimens	174	98	88	35
fragments		118		71
Breakage				
posterior	26	14	39	6
anterior	2	4	1	11
lateral	9	8	6	0
umbo	62	50	1	0
ventral	5	0	1	2
chipped	15	8	6	7
cracked	1	0	0	0
whole	67	36	29	9
O. paraboloides	1	0	7	1
umbo	0	0	7	1
lateral	1	0	0	0
O. simplex	3	1	0	0
umbo	1	1	0	0
lateral	2	0	0	0
***Caulostrepsis* isp.**	2	3	0	0
posterior	1	2	0	0
lateral	1	1	0	0
***Caulostrepsis*? isp.**	1	1	0	2
posterior	0	0	0	1
lateral	1	1	0	1
boring incomplete	1	0	3	2

Sorting of left and right valves of C. edule and S. subtruncata. There were more left valves collected than right valves for both of those species. A chi-squared test (Table 2) indicates that there is a significant difference. This is most likely caused by hydrodynamics. When the shell becomes disarticulated, the valves are carried contrarily in the prevalent current regime and to different sites, including both offshore and onshore.

Table 2. The results of chi-squared tests to determine significant similarities and differences between parameters. Significant differences are displayed **bold**.

	Chi-square	p-value
Breakage apex ***C. edule* vs *S. subtruncata***	**2090**	**<0.01**
Overall breakage *C. edule* vs *S. subtruncata*	1.30	>0.05
Borings ***C. edule* vs *S. subtruncata***	**11.40**	**<0.01**
Caulostrepsis isp. boring *C. edule* vs *S. subtruncata*	0.225	>0.05
Uncompleted borings ***C. edule vs S. subtruncata***	**48.13**	**<0.01**
Apex boring ***C. edule* vs *S. subtruncata***	**48.06**	**<0.01**
C. edule **left valves vs right valves**	**21.77**	**<0.01**
S. subtruncata **left valves vs right valves**	**64.87**	**<.,01**
C. edule borings left valves vs right valves	0.05	>0.05
S. subtruncata borings left valves vs right valves	0.74	>0.05

Exquisite preservation of E. americanus. Articulated shells of *E. americanus* were common; many still contained the soft tissues of the bivalves (Table 3). This suggests they were washed up very recently, an event that may have been the cause of widespread, simultaneous death. This is supported by the absence of any barnacles or other encrusters on the shells, an otherwise a well-known phenomenon on this beach (Donovan, 2007, 2011, Donovan *et al.*, 2014). Minimal post-mortem residence on the shallow marine sea floor and, subsequently, on the beach, is inferred

Table 3. Data on the collections of *Ensis americanus* discussed herein. Five shell-rich sites were collected, numbered 1-5 (site # 3 did not produce *E. americanus*).

Location	Total	Articulated broken	Articulated whole shell	Disarticulated broken	Disarticulated whole valves
1	52	13	29	10	0
2	45	19	22	4	0
4	33	6	25	2	0
5	40	14	25	1	0

Other observations. The distribution of borings in the left and right valves for both *C. edule* and *S. subtruncata* were not identical (Table 1), although differences were not statistically significant (Table 2). Overall breakage and infestation by *Caulostrepsis* borings between *C. edule* and *S. subtruncata* were also found not to be significant.

CONCLUSIONS

1. All of the shells of *C. edule* and *S. subtruncata* were disarticulated into separate left and right valves, indicating a long residence time on the beach. This was supported by moderately common breakage of the umbo in *Cerastoderma edule*.

2. There were more left valves collected than right valves of disarticulated *C. edule* and *S. subtruncata*, indicating post-mortem hydrodynamic sorting.

3. Some *C. edule* and *S. subtruncata* valves had *Caulostrepsis* isp. borings in them, which are domiciles produced by polychaete annelid worms after the death of the bivalve. *Oichnus* ispp. borings are most probably predatory and thus pre-mortem, but no shells of predatory (or other) gastropods were found. There were at least two groups of predators on bivalves, indicated by two different morphologies of predatory borings, *O. simplex* and *O. paraboloides*.

4. *Ensis americanus* shells were mostly articulated, some retaining soft tissues; none were bored or encrusted, all suggesting a recent mass death event, probably storm excavation. *Cerastoderma edule* and *S. subtruncata* have more robust shells than *Ensis americanus*, which favours their long residence on the beach.

ACKNOWLEDGEMENTS

Collection and analysis of data and drafting of an initial report, were the equal responsibility of A.L.H. and M.R.V.; photography and preparation of the typescript for publication was undertaken by S.K.D.

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GEOLOGICAL SOCIETY OF NORFOLK WEBSITE

The Geological Society of Norfolk (GSN) website can be found at:

http://www.norfolkgeology.co.uk

The contents and abstracts of the Bulletins, starting in 1953, are all available for download on the website. Many back issues are available in print form, see p. 44.

The society also has a Facebook page and an Earth Science Database containing over a thousand articles relevant to the geology of Norfolk.

AN ALTERNATIVE INTERPRETATION OF THE GEOLOGY OF THE LYNFORD MAMMOTH SITE, NORFOLK

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ABSTRACT

An alternative explanation is given of the geology of the mammoth site at Lynford, Norfolk, suggesting that a solutional depression is responsible for the organic sediments in the Wissey river terrace gravels, rather than a palaeochannel (Boismier et al.*, 2012). The value of extensive geological investigations around archaeological sites is shown by the discovery during the excavations of substantial thickness of sands to the south of the site, at a higher level than the terrace gravel, and banked against Chalk. These are comparable to sand at similar heights in the valleys of the Wissey tributaries to the north, the Little Ouse and the Nar valley. They are interpreted as deposits of proglacial lakes in the river valleys, ponded by ice of the Fenland glaciation in the Wolstonian cold stage.*

INTRODUCTION

The mammoth site in the valley of the Wissey river at Lynford, Norfolk (Fig. 1), is exceptionally interesting, with its wealth of archaeology, palaeontology and data relating to the environment of the time, mid-Devensian, treeless, with a continental cool climate. The site, with the stratigraphy described by Boismier *et al.* (2012), Boismier (2012a,b) and Lewis (2012), displays a sequence of sands and gravels of a low terrace of the river, comparable to the low terrace found in the Gadder river to the north, a tributary of the Wissey river.

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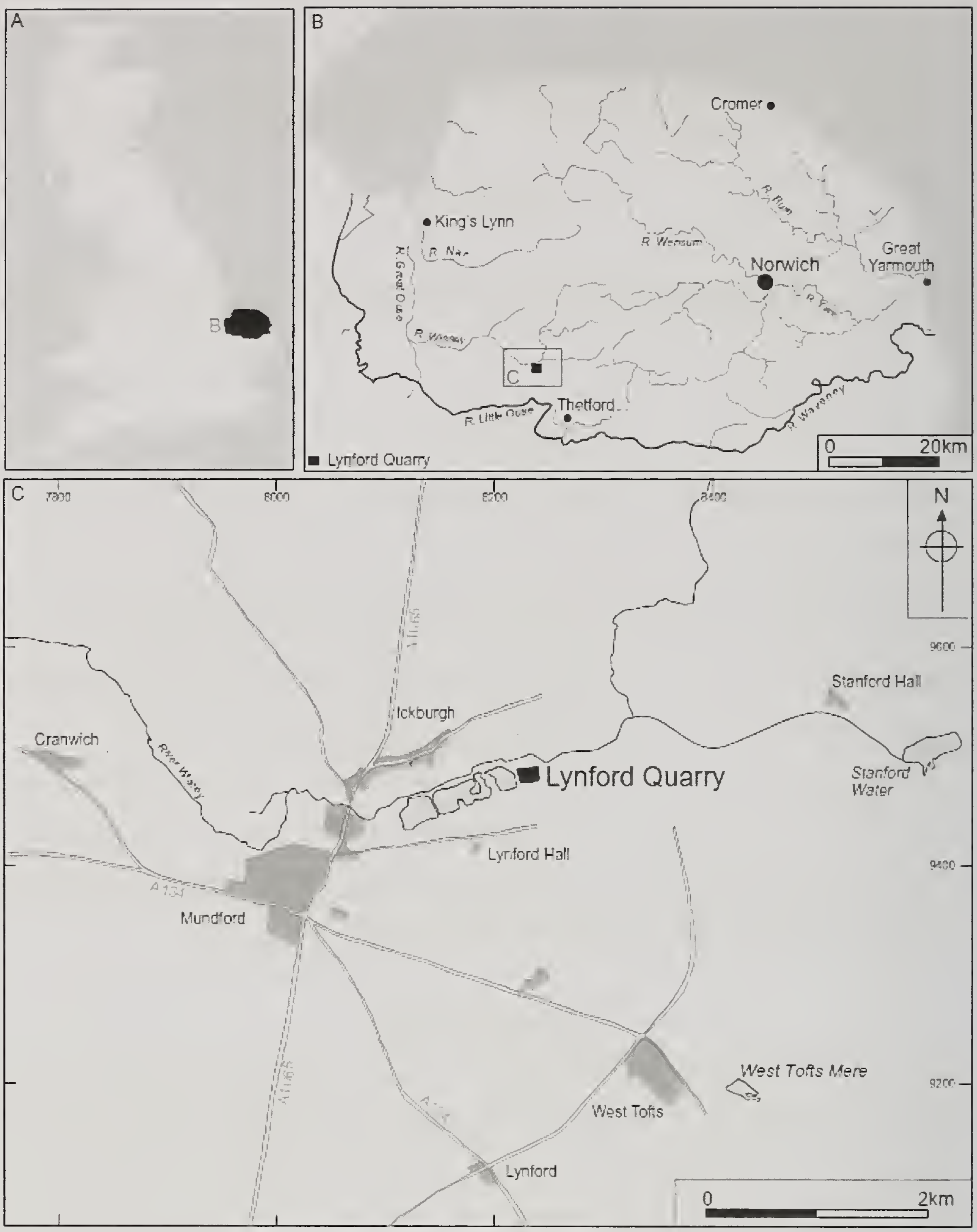

Fig. 1. The Lynford quarry site in its regional setting, from Boismier *et al.* (2012) © Historic England Archive. Reproduced with permission.

The sediments which held the rich archaeological and palaeontological finds were interpreted as part of a palaeochannel within the fluviatile sands and gravels of the low terrace, representing 'a meander cut-off, or oxbow, with still or very slow-flowing water'. Also, 'Large objects, such as bones, entered the channel periodically from the adjacent land surface by processes such as bank collapse.' It was noted, however, that no such bank areas were found to be preserved.

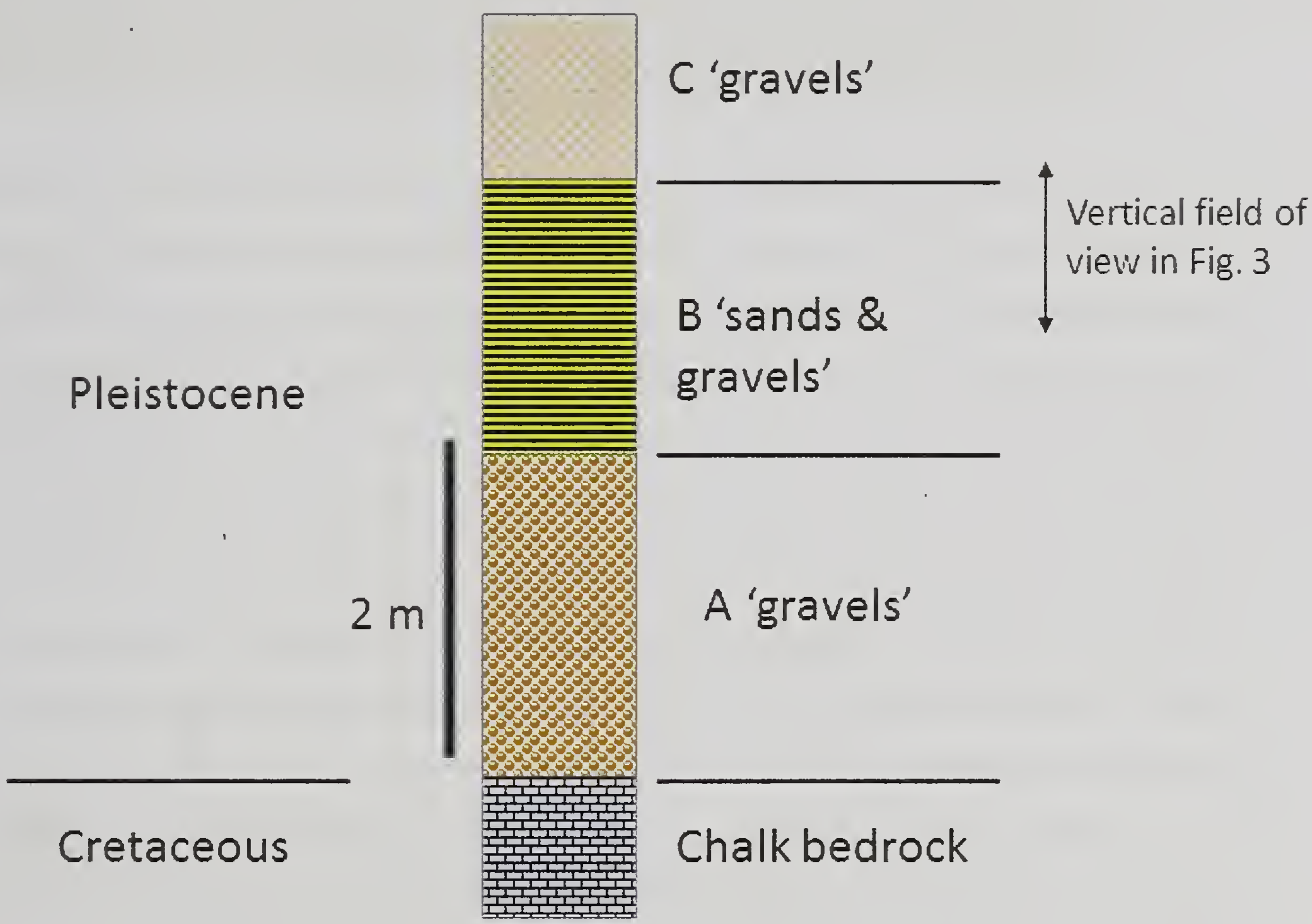

Fig 2. Schematic stratigraphy for the Lynford site, showing Facies Associations A-C as used in Boismier *et al.* (2012). Facies Association B is the unit of interest in this paper.

In outline the stratigraphy at the site is straightforward (Fig. 2; Facies Associations of Boismier *et al.* (2012)). There is a lower bed of sands and gravels up to a few metres thick (Facies Association A), which rests on an irregular surface of Chalk or reconstituted Chalk at levels varying from c.4.5m to 8.5m O.D. There is then a depression, the palaeochannel, containing a sequence of sediments (Facies Association B), up to c. 2m thick. These are overlain by a further series of sands and gravels (Facies Association C), contributing to the terrace, to a height in the valley of around 13m O.D.

The importance of the site lies in the archaeology and palaeontology of the sediments filling the depression, the Facies Association B sediments of Boismier *et al.* (2012), especially the bed B-ii:03 (Fig. 3), with a thickness up to c. 0.5m. At a distance this bed appears as a dark matrix-supported diamicton, with many flints. It is the interpretation of this bed which is critical to the understanding of the site.

An alternative explanation of the stratigraphy, explored here, is one which involves the presence of a solutional depression related to the Chalk, rather than a palaeochannel related to a meander cut-off of the Wissey river of the time. Such features commonly occur in the Breckland, along the valleys and on interfluves. They occur, for example, upstream of Lynford in the Wissey valley and its tributaries, in the tributary valleys of the Wissey north of Gooderstone (e.g. Wellmere Pit (West 2015)), and in the Little Ouse valley. They may be depressions containing water perennially or periodically, or they may be dry. They may be associated with springs, which are also present upstream and downstream of Lynford in the Wissey valley.

Sediments with an organic content, or totally organic, may occur within sequences of inorganic sediments such as fluviatile sands and gravels as a result of various processes. There may be autocthonous organic sediments deposited in pools, as may be those of transitory ox-bow ponds, or sediments may accumulate in depressions formed by the melting of ground-ice (e.g. icings) or by solution of underlying Chalk (termed solutional depressions, sink-holes, dolines). The stratigraphy within such depressions may be complex. In dolines the sediments

Fig. 3. Field photograph showing the upper 0.5 m of Facies Association B sediments including the dark coloured Bed B-ii-03. Note that in this section Bed B-ii-04, interpreted as a sediment gravity flow by Boismier *et al.* (2012) is not present. Red and white scale divisions are 10 cm. Photograph courtesy of J.E Andrews, taken 23 April 2002.

are predominantly allochthonous, associated with the collapse of the underlying Chalk, or they may show stratification related to the hydrology of the depression. Springs may be related to such solutional depressions. The complexities of collapse and rising water from the Chalk lead to processes such as gravity flow, injections or diapirs, and sediments varying from diamictons to stratified inorganic sediments.

To consider this possible explanation further, the following points are raised, based on the detailed descriptions and figures (noted below) provided by Boismier *et al.* (2012).

FACIES ASSOCIATION B SEDIMENTS

Bed B-ii:03 of this Association (Fig. 3), the major source of the archaeology and palaeontology, is a complex sediment, with a low organic content. Basically it appears to be a matrix-supported debrite, originating, at least in part from sediment flows from the margins of the depression. The bed intervenes between beds of inorganic sediments indicating varied aquatic conditions before and after its formation. Such may also have occurred during its formation. The bed is described (Boismier *et al.* 2012) as a 'detrital fine-grained silty sand (organic mud), predominantly massive with fine alternating discontinuous parallel-sub-parallel laminae of sand and organic matter in upper 0.20 m, laterally variable densities of medium to coarse gravel and cobbles and lenses of stony organic sand partially interbedded with the sediment flow gravity deposits of B-ii:04.'

The complexity must result from the additions to the debrite of a sedimentary component associated with varying water levels, including fragmental organic sediments and fossils related to an aquatic environment. There appear to be no autochthonous organic sediments. Added to all this is the likelihood of the effects of bioturbation, during and after deposition, with the incorporation of fossils derived from regional and local terrestrial and aquatic biota.

The margins of the debrite of bed B-ii:03 interdigitate with sand and gravels occupying a slight depression on a slight slope. Figure 4.3 of Boismier *et al.* (2012), reproduced here as Figure 4, is particularly informative, showing vertical distribution in bed B-ii of materials in a west to east transect and in a south to north transect. The latter shows three lines of concentrations of clasts, etc. dipping south, at a low angle, each of which may reflect a period of filling of the depression. The former shows what may be the headwards parts of two such flows on a west to east transect, which dips westwards. The orientation of these concentrations of clasts may relate to post-depositional solutional depression, centred to the west.

The depression containing the debrite may then be interpreted as a low area, receiving diamicton from slope activity, with a water level within the depression sufficient to preserve the fossil content of the debrite, but subject to changes of level, such as are found in solutional depressions in Breckland today.

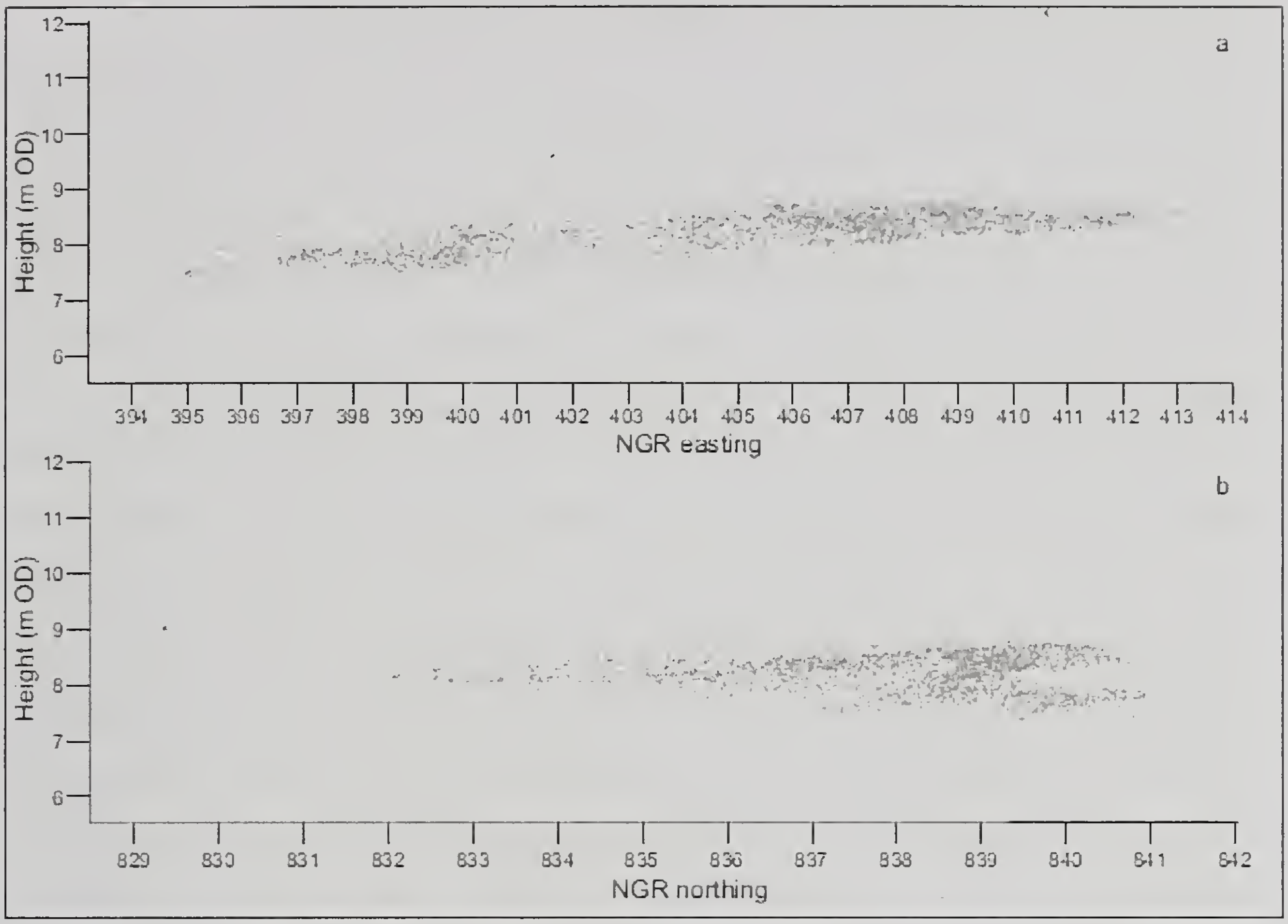

Fig. 4. Vertical distribution of materials within Facies Association B-ii sediments. a) Longitudinal E-W profile and b) a transverse N-S profile. (Fig. 4.3 of Boismier *et al.* (2012, © Historic England Archive). Reproduced with permission.

MOVEMENTS OF SEDIMENT

The excavations recorded sandy and gravelly gravity flow sediments within bed B-ii, noted as related to bank collapse at the margins of a palaeochannel. Clusters of artifacts and humanly modified vertebrate remains are identified and related to multiple depositional episodes and the variable preservation of the latter related to time spent on or within bank sediments before final burial. An alternative explanation would regard these gravity flow sediments as related to collapse at the margins of the depression as a consequence of solutional depression over time. The question of the preservation of banks would not arise. Further, if local permafrost

had been present, for which no evidence is presented but is a possibility, any upwelling of water would have caused thermal degradation, which would have led to multiple slumping over time at the margins of the depression.

HYDROLOGY

As mentioned above, springs dependent on the Chalk aquifer are not uncommon in the Wissey valley. Andrews (2012) noted, in respect of the Lynford groundwaters, that the base of the organic unit (bed B-ii:03) probably reacted mainly with up-flowing chalk groundwater. The occasional stratified sediments of bed B-ii may reflect the changes of water level in the depression over time, a character of Breckland meres. That saturated sediments were present at times is shown by the wide distribution of gravity flow sediments and also by the presence of a diapir (Boismeir *et al.*, 2012; figs, 2.11, 2.12, 2.15) which divided the dark 'organic' bed (B-ii:03). Near the southern margin of the diapir, a load cast (drop soil feature) is present with a particularly large clast (flint) at the base. The loading which produced this must have resulted from the gravels which came to overly the depression.

PALAEONTOLOGY

The excavation report (Boismier *et al.*, 2012) contains a number of significant authoritative reports on the fossil fauna and flora, recorded mainly from the debrite of bed B-ii:03. Certain points may be considered here in relation to the interpretation of the stratigraphy.

The very rich coleopteran beetle fauna is described by Coope (2012). He was surprised so many of the beetles found were xerophilous, existing in dry habitats, although the sediments were water-laid. Terrestrial dung beetles were especially well-represented, as might be expected. On the other hand, carcass beetles were remarkably rare and the assemblage also lacked species associated with dried-out carcasses. Coope suggested the possibility that mammalian remains had become rapidly submerged in the pool 'where they would have been inaccessible to these wholly terrestrial insect species'. The collapse of marginal

sediments and associated soils into the depression would explain these significant points.

Schreve *et al.* (2012) considered that the orientation of the vertebrate material showed no discernible preferred orientation, implying that there had been little disturbance of the assemblage by fluvial activity after deposition, which would accord with deposition in a solutional depression. Lister (2012) suggested the possibility that miring could account for the age/sex distribution of mammoth fauna.

Green (2012) describes the palynology of the site, with three pollen diagrams through bed B-ii:03. Taken overall these indicate the local presence of predominantly open calcareous grassland; the division of the diagrams into local pollen zones indicates variation possibly principally related to taphonomy of the pollen assemblages. The regular presence of the soil fungus *Glomus*-type remains may be related to collapse at the margins of the site, while spores of a dung fungus, *Sporomiella,* are associated with populations of herbivores. The presence of pyrite framboids are indicative of stagnant, anaerobic water. Additional reports on the macroscopic plant remains (Field 2012) and molluscs (Keen 2012) supply information on the varying hydrology of the depression, with wet and drying-out conditions. The large variation in the numbers of *Pupilla muscorum*_in various samples recorded by Keen follows from the complexity of deposition of the various sediments in the depression.

SANDS

The test pits reported by Lewis (2012) reveal a series of sands banked against Chalk to the south of the site, at a higher level (to 20m O.D.) than the low terrace. Up to 6m of sand, predominantly fine and medium, were recorded and two OSL dates determined. The height and constitution of the sands bear similarities with those found in substantial thicknesses in the valley of the Little Ouse to the south (West 2009), in the Wissey tributary catchments north of Gooderstone and in the Nar valley (West 2015). These sands were interpreted as deposits of proglacial lakes in the west-draining river valleys of the area, ponded by the ice of the Fenland

glaciation (Tottenhill glaciation) of Gibbard *et al.* (2009, 2012a & b) at c.160kyr in the Wolstonian cold stage. The OSL dates (169 & 176 kyr) from the sands at Lynford offer support to this interpretation.

CONCLUSIONS

The evidence considered above provides a case for a re-interpretation of the Lynford site as a place where a solutional hollow formed, and which became a place for miring of large vertebrates, together with the preservation of a very varied fauna and flora of a time in the mid-Devensian cold stage. How this interpretation, impossible without the thoroughness of the excavation reports, affects the understanding of the archaeology of the site, I must leave to others. But the reports show the site also has geological significance of its own. First, in demonstrating processes related to river terrace accumulations, and secondly, showing the value of extending investigations beyond the immediate area of excavation in order to secure the geological background of the site.

ACKNOWLEDGEMENTS

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IMAGING PERIGLACIAL STRIPES USING GROUND PENETRATING RADAR AT THE 'GRIM' TRAINING SITE, GRIME'S GRAVES, BRECKLAND, NORFOLK

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ABSTRACT

The geological structure of periglacial patterned ground made visible by heather 'tiger' stripes at the GRIM Military Training Site, Breckland, Norfolk was investigated using Ground Penetrating Radar. A tripartite deposit model comprising an upper pellet chalk, a gravelly diamicton and a lower chalk rubble, overlying bedrock Upper Chalk is proposed. Frost cracks active during the Devensian Stage appear to have allowed the diamicton to 'heave' to the surface during solifluction. Coversand has been deposited in the gullies formed by the frostcracks during the Devensian. It is the acidic coversand that supports the growth of heather and makes this site of both geological and ecological interest.

INTRODUCTION

The area known as Breckland is centred on Thetford, and covers about 1000 km^2 of East Anglia in southwest Norfolk and northwest Suffolk. It one of the driest areas in England, with an annual precipitation of around 530 mm; its climate is almost continental compared to the oceanic climate experienced over much of the British Isles. Breckland comprises an area of somewhat infertile sandy soil developed on relatively thin coversand overlying various glacial deposits and Upper Cretaceous Chalk (Holywell Nodular Chalk Formation and New Pit Chalk Formation; Moorlock et al., 2003) bedrock, which forms a plateau about 30-45 mOD. The weathered surface of the chalk bedrock is often mantled by a unit of periglacially disturbed chalk pellets in a matrix of chalk putty described

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herein as 'pellet chalk'. Angular frost-shattered chalk clasts in contact with the rockhead often form a unit of 'brecciated chalk', which sometimes passes upwards into 'pellet chalk'. The surface of the underlying weathered pellet chalk is rarely flat, and often exhibits troughs and ridges (patterned ground) that are thought to be the product of periglacial activity during the last glacial period (Devensian) (Bateman et al. 2014).

It appears that the well-rounded and well-sorted coversands, with a mean particle size of c. 175 μm, blew into Breckland from the glacial margin towards the end of the Devensian, between the Last Glacial Maximum (LGM) *c*. 18,000 years BP and the start of the Holocene c.11500 years BP (Chorley *et al*., 1966). Indeed, inland dune fields were active in Breckland not only during the last glacial period, but from mid-Holocene times onwards (Bateman & Godby, 2004).

During the Devensian, the proximity of the North Sea ice sheet at Hunstanton on the present Norfolk coast would have brought intense periglacial activity to Breckland, leading to brecciation of Chalk bedrock, and heaving of the permafrost active layer resulting in the formation of patterned ground (polygons and stripes) (Nicholson 1976; Ballantyne & Harris 1994). The Breckland coversand is of variable thickness, and analyses by the authors show that the sandy soils formed upon it have pH values that vary from >pH 8 where influenced by cryoturbated pellet chalk, to <pH 4 where developed on deep coversand. Today much of the region is dominated by commercial forestry, but in un-forested localities such as Military Training Areas, deeper patches of coversand usually support heather (*Calluna vulgaris*) and acid tolerant grassland. However, in closely adjacent areas with brecciated pellet chalk close to the surface, bio-diverse calcareous grassland is supported (Watt *et al.* 1966). The flora and vegetation patterns of this heathland can vary over small distances (<10 m) as a consequence of these diverse soil characteristics. Lowland heath is one of the most threatened habitats in England. Breckland is designated as an Environmentally Sensitive Area, and contains several Sites of Special Scientific Interest (Marrs & Britton, 2000).

STUDY SITE

The GRIM Military Training Area (a Danger Area with severely restricted access due to the possible presence of unexploded munitions), exhibits closely juxtaposed acid heath and calcareous grassland (c. 30 – c. 20 mOD) arranged in 'tiger' stripes extending down

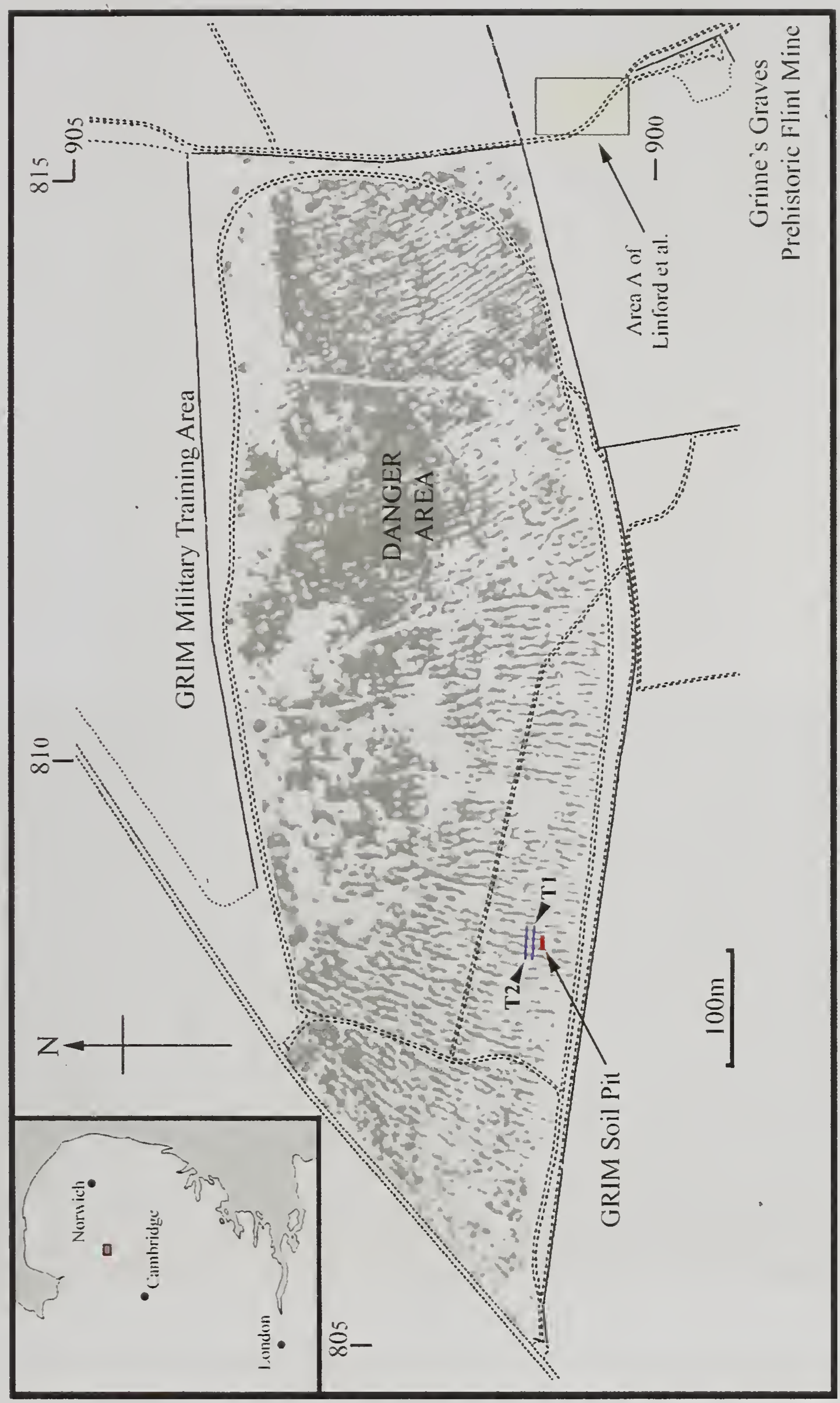

Fig. 1. GRIM Military Training Area showing distribution of heather stripes from aerial photography, location of the GRIM Soil Pit and GPR transects (T1 & T2). The location of the Grime's Graves Prehistoric Flint Mine is also shown with the position of 'Area A' from the GPR survey of Linford *et al.* (2009). Aerial image © Cambridge University Collection of Aerial Photography.

a gentle slope (2-3°) towards the floor of a small dry valley opposite the Grime's Graves Prehistoric Flint Mine (see Fig. 1). The vegetation stripes closely follow periglacial patterned ground, a section through which is visible at the GRIM Soil Pit (NGR TL 80845 90105; Fig. 2). A description of the sediments exposed in the soil pit section is shown in Figure 3. Although red/brown coversand can be clearly seen to rest in a gully between flanks of contorted brecciated pellet chalk, it is underlain by a brown diamicton comprising contorted gravel, sand and pellet chalk. Boreholes by the authors along the heather stripes have shown that coversand is rarely deeper than c.1 m, and that pellet chalk is usually encountered after only c. 30 cm in the intervening grassy swards. Large flints, often vertically aligned, often occur associated with the coversand. The nature of these and other periglacial stripes has been the subject of investigation and debate over many years.

Fig. 2. Field photograph of the GRIM Soil Pit looking NE, showing the position of a heather stripe above a gully filled by coversand and flanked by brecciated pellet chalk.

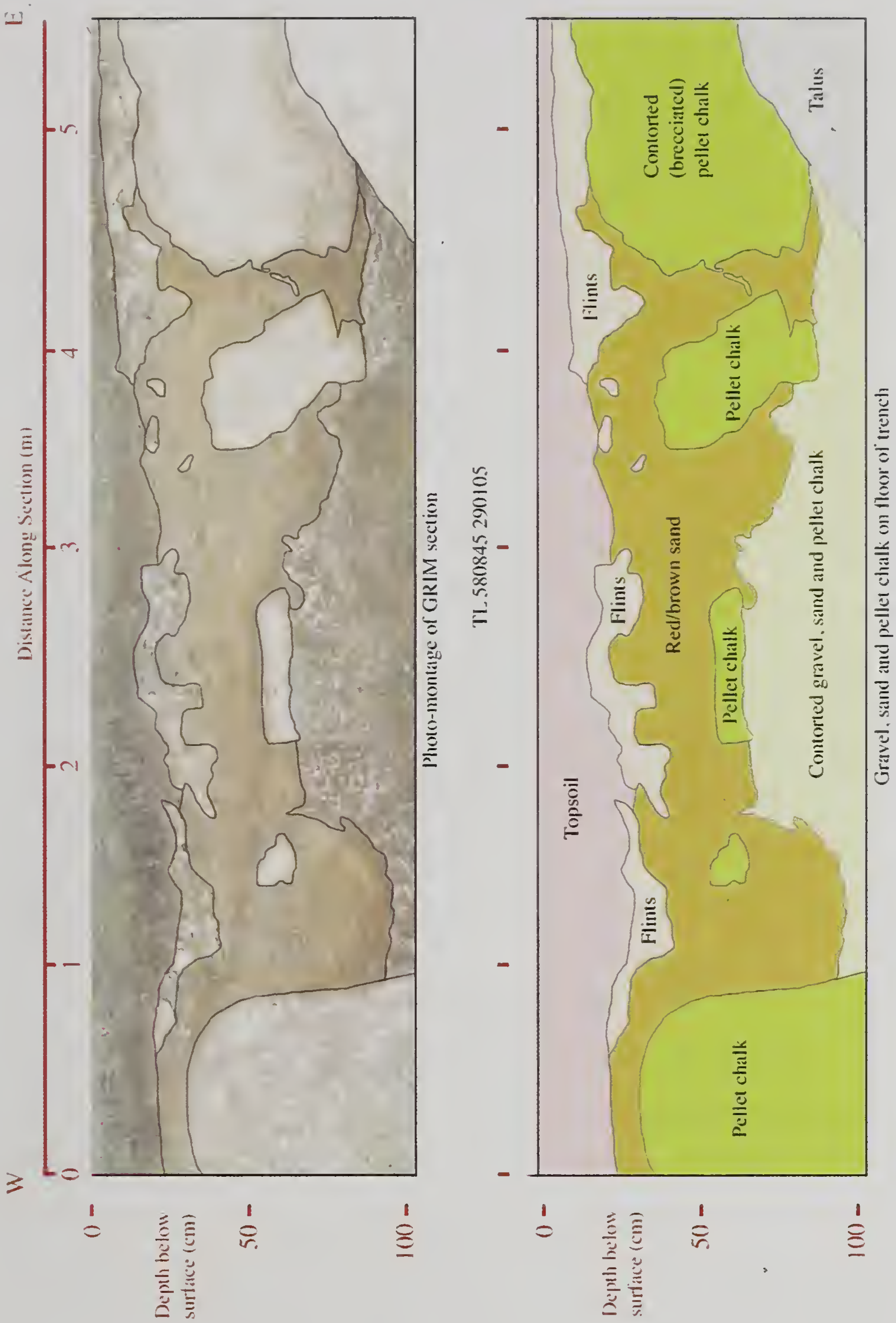

Fig. 3. Field photograph of the GRIM Soil Pit section and description of the exposed sediments.

Table 1. Radar surfaces and facies identified in this study and their interpretation.

	Description	*Interpretation*
Radar facies RF5	Moderate to high amplitude, planar, sub-parallel, continuous reflectors, truncated by RS4	Topsoil and regolith with flints
Radar surface RS4	Sub-horizontal, gently undulating surface	Unconformity
Radar facies RF4	Low amplitude, horizontal and dipping fragmented or discontinuous reflectors, truncated by RS3	Periglacially disturbed pellet (brecciated) chalk and/or coversand
Radar surface RS3	Sub-horizontal, complex sinuous, wavy or inverted, undulating surface	Unconformity
Radar facies RF3	Moderate to high amplitude, sub-horizontal, dipping, sub-parallel, sometimes discontinuous reflectors, truncated by RS2	Contorted gravel, sand and pellet chalk - diamicton
Radar surface RS2	Sub-horizontal complex sinuous or wavy, undulating surface	Unconformity
Radar facies RF2	Low amplitude, horizontal and dipping fragmented or discontinuous reflectors, truncated by RS1	Periglacially disturbed (brecciated) chalk rubble
Radar surface RS1	Sub-horizontal sinuous or wavy, undulating surface	Bedrock surface (rockhead)
Radar facies RF1	Medium to high amplitude, sub-parallel horizontal and dipping, continuous and discontinuous reflectors	Chalk bedrock

GROUND PENETRATING RADAR

The internal structure of the periglacial stripes immediately upslope of the GRIM Soil Pit has been investigated using a ground-penetrating radar (GPR) GSSI 200 MHz shielded antennae (Annan & Davis, 1976 and Davis & Annan, 1989), which offers acceptable depth penetration and excellent acuity. The GPR data has been truthed and interpreted using hand-augered boreholes. The location and altitude of the two GPR

transects (T1 & T2) were determined using a Leica GNSS SmartNet system. The GPR transects presented here show the architecture of deposits associated with the periglacial landforms (Figs 4 & 5). An average relative dielectric value (er) of 8, used for initial depth conversion, was estimated from the literature (Davis & Annan 1989; Hänninen 1991; Neal 2004). Post-processing of raw data was accomplished using Radan software. The radar stratigraphy here is based on the recognition and interpretation of radar surfaces (bounding surfaces) and radar facies (bed assemblages). Five radar facies (RF1-RF5) and four radar surfaces have been identified (RS1-RS4). The radar facies are summarised in Table 1.

Figures 4 and 5 both show c. 30 m long GPR transects (T1 & T2) about 5 m apart, each crossing four heather stripes. The plots show that the area between the stripes is composed of periglacially disturbed brecciated chalk (RF4). Note that the coversand in the gullies cannot be easily differentiated by the GPR and thus must have a similar dielectric value to the surrounding pellet chalk. Beneath each stripe is a column of diamicton, comprising gravel, sand and pellet chalk (RF3). Note that this material extends down to c. 2 m depth where it joins laterally to form a stratum that underlies the upper pellet chalk. Beneath this is a separate body of material interpreted here as brecciated chalk rubble (RF2). Although this material lies in contact with the bedrock chalk (RF1) with a rockhead at 3.5- 4.5 m, it is punctuated in places by the overlying columns of gravelly diamicton (RF3).

DISCUSSION

In 2007 Ground Penetrating Radar investigations took place at Grime's Graves Prehistoric Flint Mine (Linford et al. 2009). The area of study was opposite the GRIM Military Training Area (see Figure 1), and although mainly directed at discovering hidden archaeology, some details of periglacial features were also uncovered. The 2007 GPR investigation showed the Chalk rockhead to be present at between 1 and 3 m depth, sometimes with regularly spaced deeper areas. In the present study at GRIM there is superficial coincidence between slightly higher points on the chalk bedrock reflector and the heather stripes (Figs 4 and 5). This is almost certainly caused by periglacial heaving beneath each column of diamicton. Boreholes at Grime's Graves in 2007 discovered a

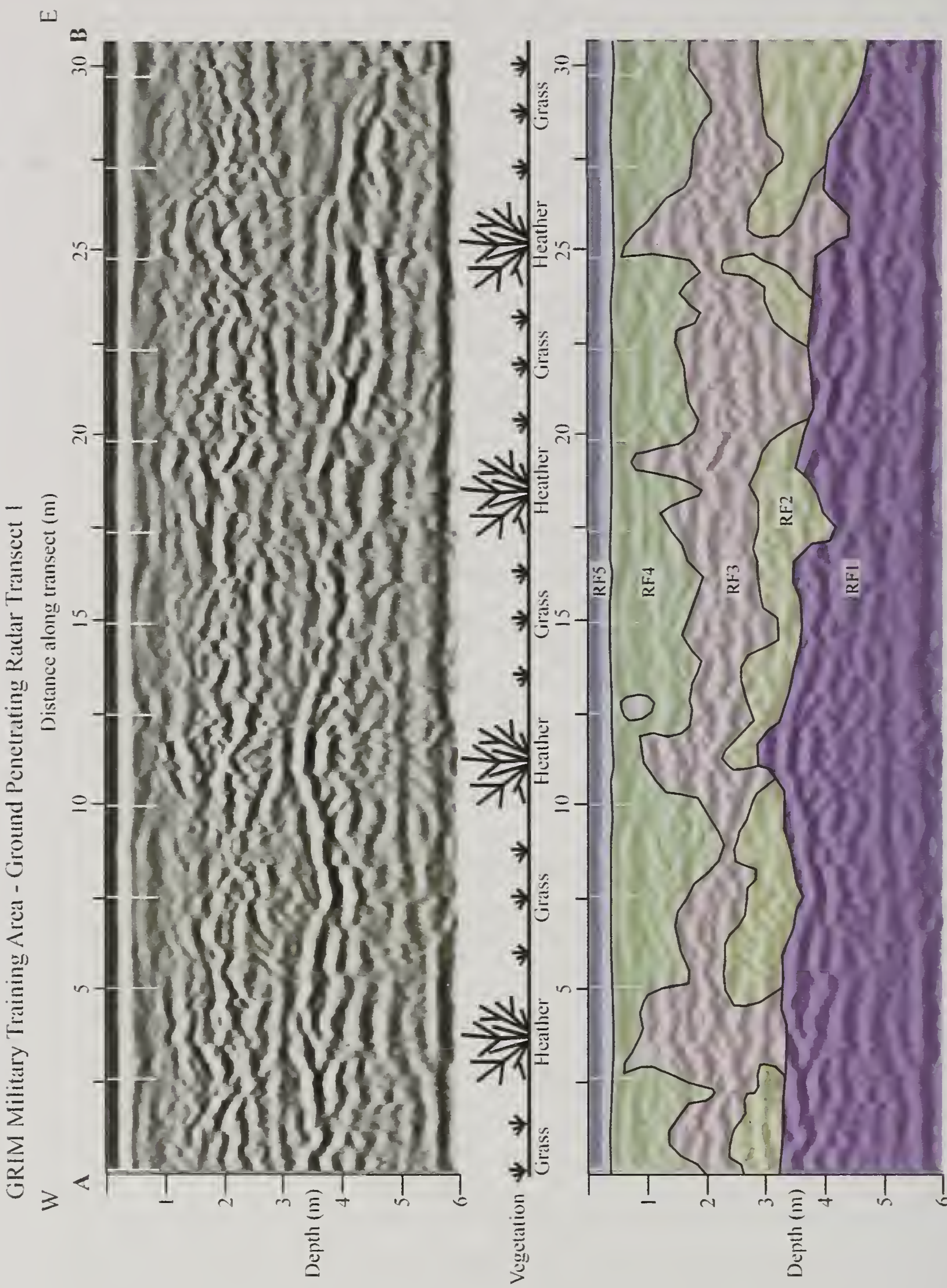

Fig. 4. Ground Penetrating Radar plot for transeet T1 showing interpretation of the reflectors and the position of heather stripes.

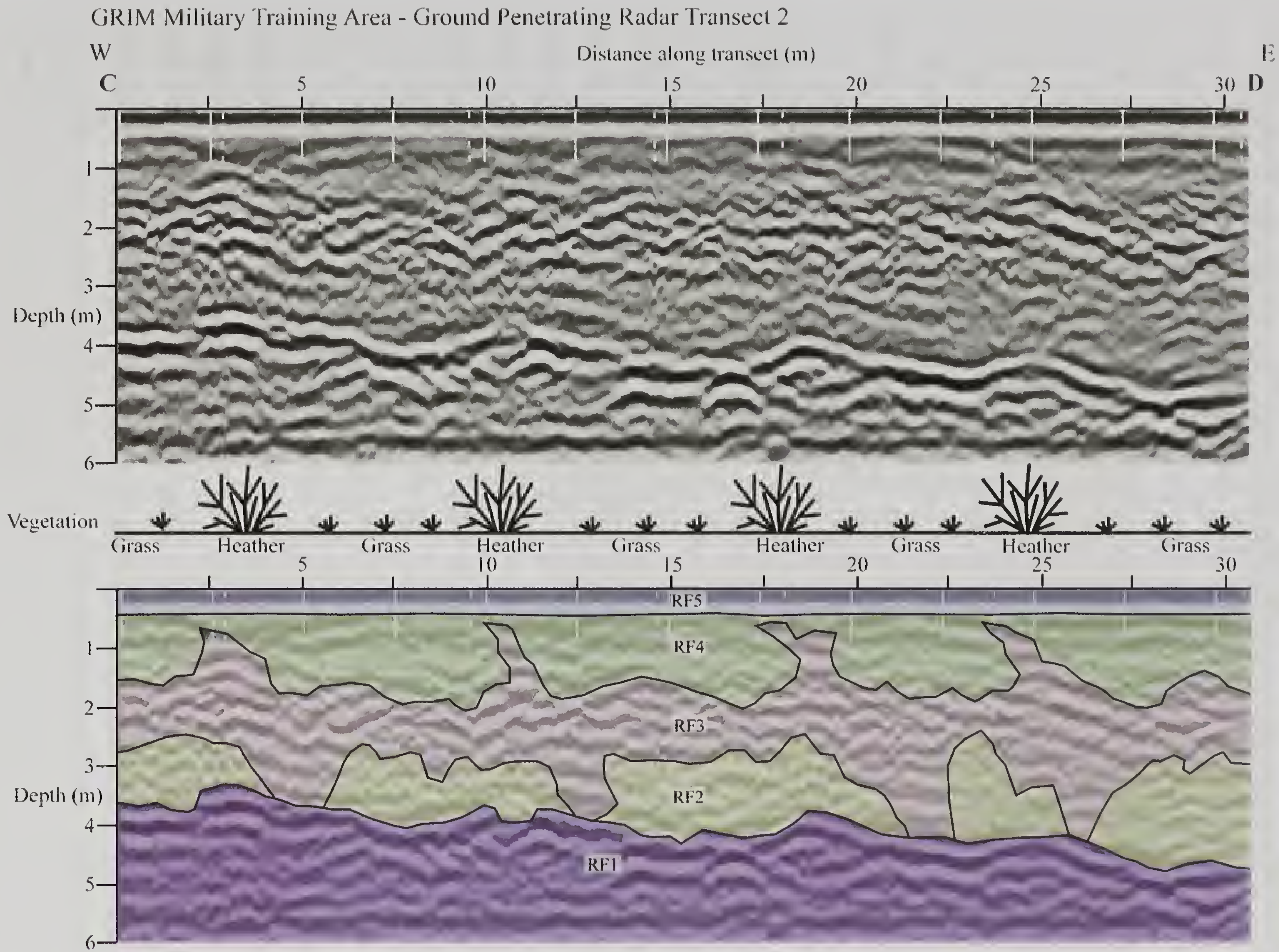

Fig. 5. Ground Penetrating Radar plot for transect T2 showing interpretation of the reflectors and the position of heather stripes.

sequence of chalk rubble and sand more than a metre thick, resting on Chalk bedrock at c. 2.5 m depth. Above this was a stratum (c. 40 cm thick) of brecciated pellet chalk, in turn overlain by c. 50 cm of coversand and finally thin topsoil. Although this sequence seems superficially similar to that at the GRIM Military Training Ground, it appears that there is an absence of gravelly diamicton at this site between the basal chalk rubble and the overlying pellet chalk. The block sections of Breckland stone stripes created by Nicholson (1976), and reproduced in Ballantyne & Harris (1994; p.97 fig 6.15) closely represents the situation seen at Grime's Graves. In contrast, several sites in Breckland with periglacial stripes and OSL dated by Bateman et al. (2014) were formed by coversand overlying a chalk diamicton. This seems to suggest a far simpler genesis of periglacial features, and indeed Bateman et al. (ibid) conclude that these features resulted from repeated periglacial activity within the Devensian Stage.

A summary interpretation of the GPR reflectors and deposits beneath heather stripes at the GRIM Military Training Area is shown in Figure 6. The heather stripes at the GRIM Military Training Site appear to be closely associated with c. 1 m thick accumulations of acidic (<pH 4.5) coversand that occupy deep gullies developed in frost cracks on top of heaved columns of gravelly diamicton extending down 3 – 4 m to the Chalk bedrock. Note that the frost cracks aligned with the heather stripes appear to have allowed the gravelly diamict to 'heave' or 'boil' to the surface between 'rafts' of upper pellet chalk. There do not seem to be ice wedge casts associated with the frost cracks. The tripartite nature of the deposits overlying the Chalk implies that solifluction must have brought regolith material with different compositions into the area at different times. This strongly implies a polycyclic origin for the chalk rubble, pellet chalk and the intervening gravelly diamicton, either within the Devensian Stage, or potentially encompassing several Pleistocene glacial periods. The basal brecciated chalk rubble must presumably be the product of the original sub-aerial exposure of the Chalk bedrock to periglacial conditions. The overlying gravelly diamicton must have come from a source upslope to the north. It appears to comprise an admixture of flints, coversand and pellet chalk. The upper pellet chalk must also come from a location upslope, presumably from an exposure of Chalk bedrock.

During the last glacial period, the periglacial regolith at the GRIM training site must have been progressing down the low-angle slope through repeated cycles of

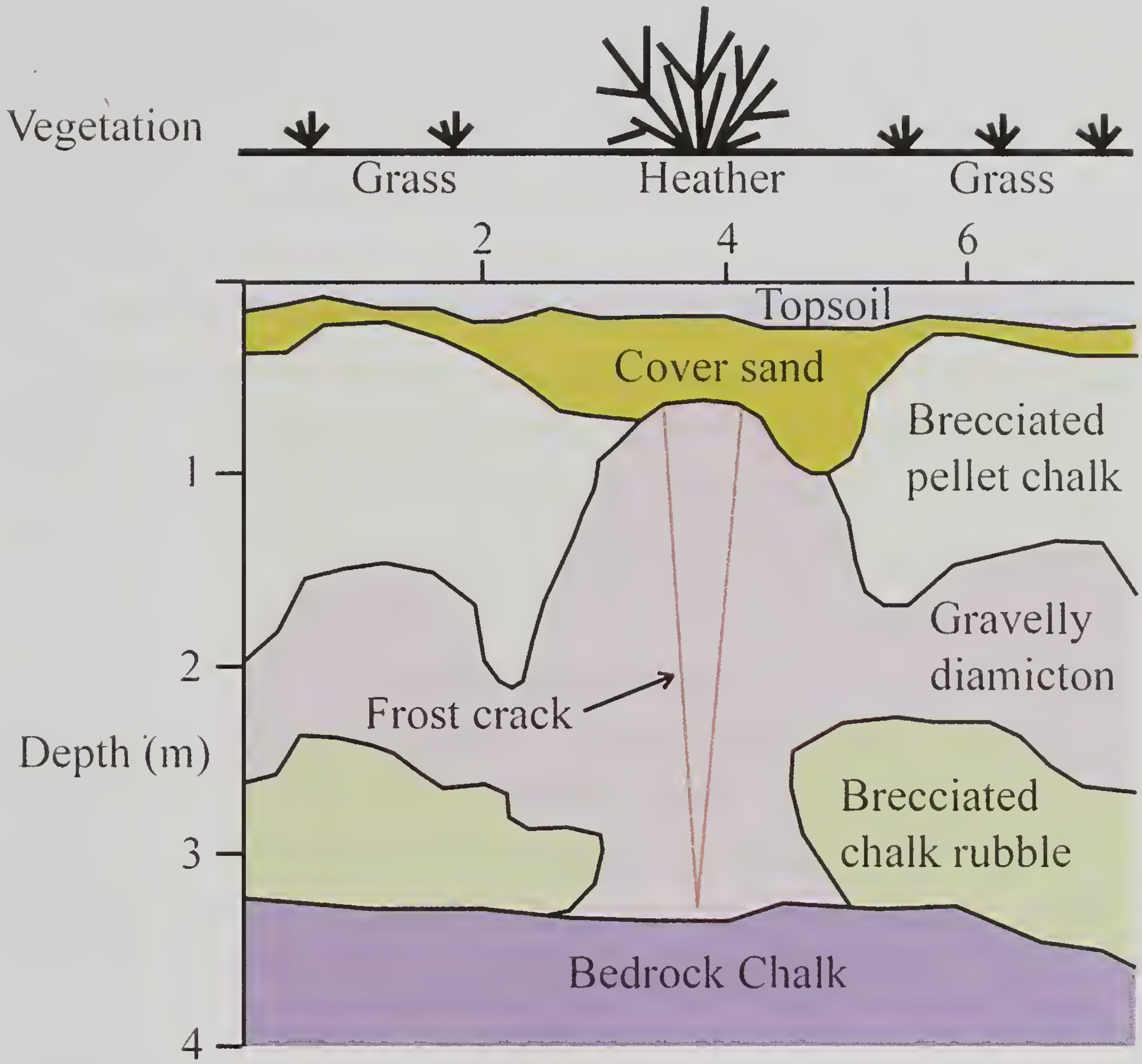

Fig. 6. Summary interpretation of the GPR reflectors and deposits beneath heather stripes at the GRIM Military Training Area.

freezing and thawing, rather like a slow-moving conveyor belt. Polygonal frost cracks appear to have been elongated by the down-slope movement of the regolith to form a 'stretched reticulum' and ultimately the 'tiger stripes' that we see today. Coversand must have been deposited into the gullies formed by the frost cracks as aeolian sediment and potentially reworked by colluvial processes. It seems likely that drainage was once active in the small valley at the foot of the slope in order to remove the regolith material delivered by solifluction processes.

In this study, a combination of boreholes, sediment descriptions from the GRIM Soil Pit and Ground Penetrating Radar have been used to image and understand complex periglacial structures beneath heather stripes that form above gullies filled by coversand.

The impetus to publish this short account was the perceived fragility of the site. The delicate nature of the heather stripes is maintained by carefully managed grazing, but the constant issue of encroachment by both scrub and bracken threatens to obscure these once impressive features. The GRIM Soil Pit is also becoming overgrown and degraded. However, the periglacial features at GRIM have survived the entire Holocene with its attendant changes in climate and vegetation, and they will undoubtedly continue to offer geological and ecological interest for those lucky enough to visit them. Access to the GRIM Military Training Site is tightly controlled, being a Danger Area, with the possibility of unexploded munitions. Today, the heather stripes are best viewed by looking north from the Grimes Graves Prehistoric Flint Mine.

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WILLIAM SMITH'S PROBLEMS WITH THE CORRELATION OF THE POST-CHALK SECTION IN EAST ANGLIA, AS REVEALED IN HIS GEOLOGICAL SECTIONS.

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ABSTRACT

This note highlights, and offers an explanation, for a misunderstanding of the stratigraphy of East Anglia made by William Smith in his ground-breaking descriptions of East Anglian geology. Specifically, he placed the London Clay, his Unit 1 and now known to be Palaeogene in age, above the sands, clays and gravels (his Units 2, 3 and 4) that are now known to be of Pleistocene age.

Banham's (2014) paper on two of Smith's East Anglian sections provides an interesting insight to the industriousness of William Smith and the geological world of the early nineteenth century. However, the paper does not highlight the major stratigraphic error made by Smith (which is illustrated at 'Porland Hill' on the section through Norfolk), namely that Smith placed his London Clay (Unit 1), now known to be Palaeogene in age, above the sands, clays and gravels (Units 2, 3 and 4) that are now known to be of much younger, Pleistocene age. Banham (2014) has also applied lithological descriptions to Smith's Unit 1 which Smith actually applied to Units 2, 3 and 4.

The two geological sections described by Banham were actually not unpublished, but issued by John Cary in May 1819 (26c in Eyles' bibliography of Smith's publications, 1969; Fuller, 1995). The examples used by Banham from the Smith archive (OUMNH *Ref: WS/G/1/006*) are probably printer's proof copies, retained by Smith. A third section across Essex was issued by Smith in the same year (26b in Eyles, 1969, Fuller, 1995: see

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Fig. 1). The Norfolk and Suffolk county geological maps were also published in 1819 in *Smith's Geological Atlas* (25 and 27 in Eyles, 1969). His map of Essex was published the following year (28 in Eyles, 1969). Therefore, Smith's ideas were available directly to later geologists rather than moderated through Taylor's 1827 sections, as Banham (2014, p.37) suggests in his paper. The small sketches of Smith's sections made in a notebook by Samuel Woodward sometime after 1825 (Fig. 2) are further evidence that these ideas were readily accessible.

It is, as posited by Banham (2014, p.35), almost certain that Hodgkinson's (Suffolk) and Faden's (Norfolk) County maps informed the topography shown in Smith's sections. Faden published both of these maps (Macnair & Williamson, 2010) and Smith visited Faden in London to discuss Faden's map of Norfolk in the course of his work on the Norfolk sea breaches (William Smith Diaries, June 1805, OUMNH Ref: WS/B/005). Smith relied heavily on the part of Faden's map covering the Hundreds of Happing, Tunstead and Flegg, in his preparation and illustration of his published 1804 report to the

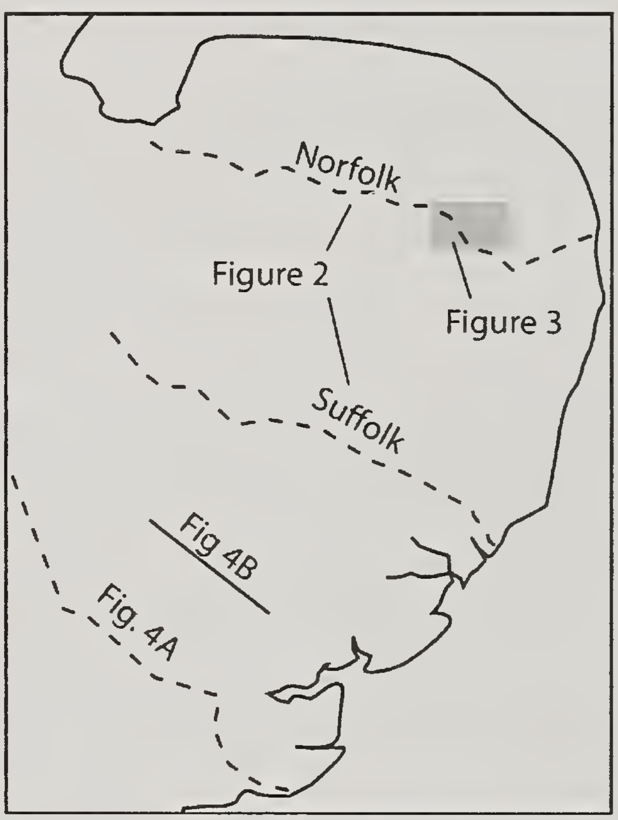

Fig. 1. Location map for sections and map extract shown in Figs 2, 3 and 4. Dashed lines refer to Smith's geological sections.

Fig. 2. Samuel Woodward's sketched copies of William Smith's sections across Norfolk and Suffolk from his unpublished notebook in the possession of the author. Probably copied sometime after 1825 from originals belonging to Dawson Turner or possibly Hudson Gurney (Woodward, 1891, p.2). Original section drawings are 15 cm wide. Note that Woodward has corrected Smith's interpretation of London Clay at Poringland.

Commissioners for Draining Hickling and Heigham Marshes (Norfolk Record Office Reference: DN/MSC 6/6, not recorded in Eyles, 1969).

Banham's (2014) discussion of Smith's stratigraphy of the post-Chalk sequence in Norfolk and Suffolk, appears to have relied heavily on the notes printed at the base of the two sections. The purpose of these notes was to comment on the local character of his units and formed only a part of the basis for Smith's stratigraphy, which was more fully discussed in his other published work, notably *Strata Identified by Organized Fossils* (1816-1819) and *Stratigraphical System of Organized Fossils* (1817). Smith used colour and number codes to identify his stratigraphical units on his maps and sections. The basis of his colour scheme is explained in *A Memoir to the Map and Delineation of the Strata of England and Wales and part of Scotland* (1815), his other books and by keys on maps. Over time he modified the numbering system for his units, and the numbers used on the Norfolk and Suffolk sections are illustrated in his *Geological Table of British Organised Fossils (1817).* Smith divided the sequence above the Chalk into two divisions in his *Strata Identified by Organized Fossils* (1816, p.1):

> "a great Sand and a great Clay (London Clay), with a general parting of Crag; but each of these is subject to considerable variations".... "the great Sand is in many places interspersed with Clay, or Brickearth, and the (great) Clay as frequently with Sand and Loam. Pebbles are common to both."

Smith believed, incorrectly, that his "great Clay"/London Clay (identified by him as Unit 1 and coloured petrol blue) lay <u>above</u> the "great Sand" (made up of Units 2, 3 and 4 and coloured yellowish brown): an error that was not repeated by subsequent authors, such as Taylor (1827). Smith defined the Crag as Unit 3, although he recognised it had a different character and occurred in different stratigraphic positions across East Anglia (*Table of British Organised Fossils 1817; Strata Identified by Organized Fossils,* 1816, p.1, 2).

Within Norfolk and Suffolk, Smith coloured only two small areas of London Clay (Unit 1) on his county maps and sections. These represented the flint-rich gravels on the tops of Porland (Poringland) Hill and Strumpshaw Hill, to the east of Norwich (Fig. 3)

Fig. 3. Extract from William Smith's Geological Map of Norfolk for the area to the east of Norwich showing outcrops of "London Clay, Unit 1" and its description from the key. Reproduced with the permission of the Geological Society of London.

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which lay on top of Smith's 'great Sand'. These two "London Clay" outcrops are also marked on his great map of 1815: *A Delineation of the Strata of England and Wales, with part of Scotland.*

Smith's interpretation poses two questions: 1) why did he believe that the London Clay was younger than the Pleistocene sediments, and 2) why did he correlate the flint-rich gravels at Poringland and Strumpshaw with the London Clay?

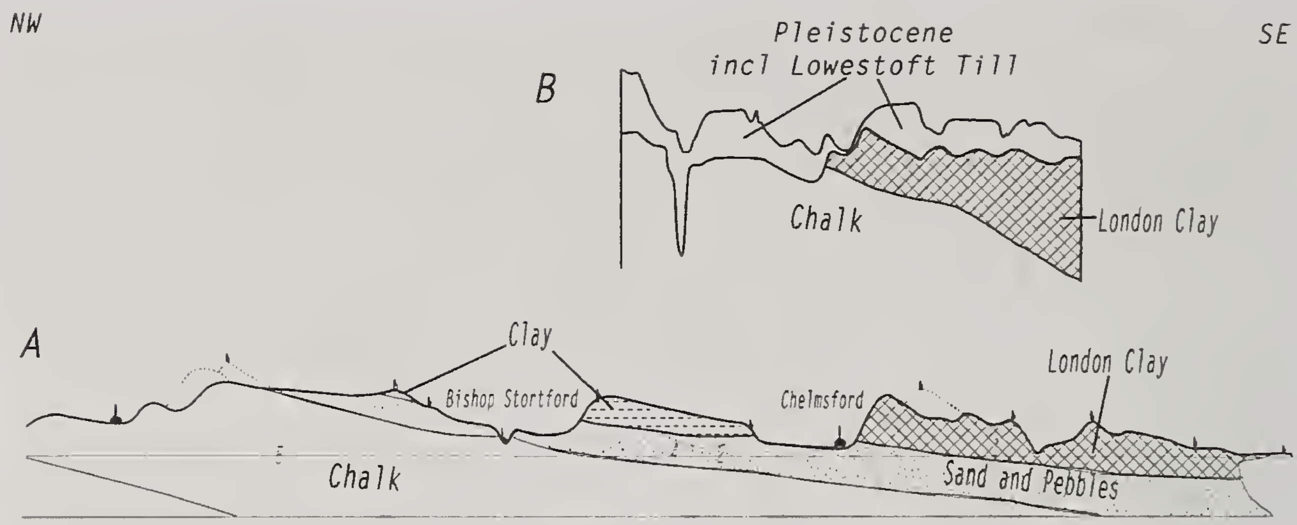

Fig. 4. Two line drawings of sections showing the different interpretations of the relationship of the London Clay to the other sand, gravels and clays above the Chalk. Section A is taken from Smith's *Geological View and Section in Essex and Hertfordshire* (1819) and B is derived from Figure 7 of Mathers & Zalasiewicz (1988) and lies ~10km to the North of Smith's section. See text for discussion.

A part of the explanation for why Smith placed the London Clay above Pleistocene sediments may be found further south in Essex on his *Geological View and Section in Essex and Hertfordshire* (1819; see Fig. 4A). The outcrop of Smith's "great Sand", Units 2 and 4, around Chelmsford lies at a lower level than his extensive "London Clay" outcrop to the east. An underlying tenet for Smith's English stratigraphy was that the strata dipped uniformly towards the east. Therefore, Smith assumed that the "great Sand" dipped eastwards at a very low angle <u>beneath</u> his London Clay outcrop to the east. He had not recognised that the western limit of his London Clay was the result of erosion prior to the deposition of the "great Sand" sediments (see Figure 4B for a modern interpretation of the sequence). The younger sediments of Smith's Unit 2, 3 and 4 in north Essex are now considered to be Plio-Pleistocene in age and composed of the marine Crag formations, the fluvial Colchester Formation, and various glacial deposits, including the Lowestoft Till. As a consequence of Smith's interpretation, any sediments that lay above the base of his London Clay to the east of Chelmsford would, by definition, be part of the London Clay in spite of any similarities they might have with sediments in

his "great Sand" Unit. This might explain why he did not record the Crag on top of the London Clay outcrop at Walton-on-the-Naze in Essex. Whilst Smith may not have seen the Crag at Walton, it is more likely that he thought it was a shelly part of the London Clay Unit that "in some instances was difficult to be distinguished from those of the Crag" (*Strata Identified,* p.3).

The deposits of Smith's London Clay Unit also contain locally thick beds of gravel, such as the subsequently named Bull Head Bed of the Thanet beds. These gravels consist of reworked flints and are similar to the flint-rich gravel at Strumpshaw and Poringland. Smith also recorded fossils from his London Clay on the Norfolk coast at Happisburgh (sediments now known to be Pleistocene in age) that included reworked ammonites and the bivalve *Tellina* (*Strata Identified* pp. 3, 4). Thus, it may be reasonable to assume that Smith correlated the rather unusual, flint-rich gravel at Poringland and Strumpshaw with the gravels in the London Clay by extrapolating strike and dip of the basal surface of the London Clay from the outcrops to the south and on the northeast Norfolk coast. Moreover, the label on the Norfolk map (Fig. 2) suggests Smith considered the hills near Norwich to be formed of "the highest strata in the County" and, by implication, analogous to the "detached hills" of his London Clay Unit around London.

Smith was clearly aware of the difficulties in correlating and mapping the post-Chalk sequence in East Anglia caused by the limited outcrops, lateral lithological variations, occurrences of similar sediments at different levels and the shortage of characteristic and widespread fossils for his units. These difficulties are reflected in a number of ways in his work. The level of detail in the descriptions of the Units varies in Smith's different publications and his definitions of the boundaries between Units 2, 3 and 4 are often generalised. Smith's uncertainty about the correlation of Units 2, 3 and 4 of the "great Sand' is reflected on his maps, where in places the boundaries within the "great Sand" terminate abruptly or are missing altogether. The definition of the coloured area on the maps can also vary, e.g., on his Norfolk map, Smith grouped Units 2, 3 and 4 together but subdivided the area on the map, not by Unit but by soil type: "the darker shade of Brown represents the Heavy Lands and the lighter shade the Sand and Heath Lands". Smith's sections do not contain a consistent or regular identification of Units 2,

3 and 4, e.g., none of the units are numbered or separately identified on his Suffolk section.

Comparison of sections A and B in Figure 4 and close inspection of Smith's maps suggest that Smith also included "clay", that today would be referred to the Lowestoft Till, within his London Clay unit in some parts of Essex and in Unit 2 of his "great Sand" division in others. Smith was able to map the extensive tracts of clay as Unit 2 across the higher and western parts of Norfolk and Suffolk although the correlation became more problematic in Essex. The stratigraphic difficulty with Unit 2 in Essex is reflected by the different coloured versions of Smith's Essex cross-section (Figure 4A). In some versions of the section, Smith's clay outcrop to the west of Chelmsford, between Roxwell and Hatfield Heath (marked Roxfield and Hatfield on Smith's section), is erroneously coloured blue for London Clay, Unit 1 (e.g., in the version reprinted in Fuller, 1995 and at www.strata-smith.com
) and in others it is coloured correctly in yellowish brown for his "great Sand' Unit, i.e., in accordance with Smith's geological map of Essex.

Banham's (2014) use of modern interpretations to separate Smith's Units 1 and 2 into a "glacial succession" and Units 3-12 into a pre-glacial succession is not based on a full understanding of Smith's Units or the problems in defining their extent. Banham's description of the post-Chalk Units, 1 to 4, (pp. 35, 36) has perhaps relied on his own interpretation of Smith's notes at the base of the two sections shown in his paper, rather than from the totality of Smith's work. For example, Banham's description of Unit 1 (i.e., what should be Smith's London Clay) as,

Alluvium, gravel and blown sand.

- *bones of large mammals found in these gravels at Costessey*
- *Breckland blown sand 'drifted from the stratum of sand over the Chalk'*
- *Blowing sand' from the Crag below in East Suffolk*

is perhaps not one that Smith would recognise as, with the partial exception of "gravel", Smith only associated these sediments with his Units 2, 3 and 4 and they are unrelated to Smith's Unit 1 ("London Clay") at Poringland and Strumpshaw. Smith's note on the Norfolk section concerning bones from large animals in the gravel near Norwich

undoubtedly refers to the "Stone Bed" at the base of the Crag at Whitlingham (*Strata identified,* p.2) and the other "Crag" pits around Norwich, i.e., Smith's Units 3 and 4, rather than to Costessey or to Smith's true "Unit 1" (at Poringland and Strumpshaw).

Smith's interpretation of the geology of East Anglia was an undoubted triumph, in spite of its shortcomings. Smith was acutely aware of the difficulties and problems with correlating the post-Chalk sediments in East Anglia and these underlying problems continued to cause controversies in Plio-Pleistocene geological research over the subsequent two hundred years.

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The photograph on the front cover is from the upper 0.5 m of Facies Association B sediments at the Lynford Mammoth Site, discussed by West in this issue of the Bulletin. Photograph taken by J.E Andrews, 23 April 2002.

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